Bushfire history from grasstrees at Eneabba, Western Australia

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Abstract

A method for reconstructing bushfire history from fire marks on grasstree stems (*Xanthorrhoea* species) has been suggested for south-western Australia. Depending on the grasstree age, the history can extend back for over two centuries. Such history is important in understanding the behaviour of bushfires and their effect on ecology; in managing them to protect people and their assets; and for nature conservation. Two critiques of the grasstree method have been published, based on its application in *kwongan* heath, a few hundred kilometres north of Perth. Both papers extrapolate their criticism to previous grasstree work in vegetation south of Perth, such as the *jarrah* forest. This paper addresses the second paper, dealing with *kwongan* data from Eneabba. I show that the pattern of agreement between fire intervals derived from grasstrees and satellite images, over a thirty year period, is unlikely to occur by chance. Data from grasstrees dating back to the 1920s show a clear lengthening of fire intervals over the twentieth century. Reasons for disagreement between grasstree and satellite data are discussed. These include the omission of some grasstree data, possible errors in grasstree interpretation, and possible errors in satellite image interpretation.

Keywords: bushfire, history, *kwongan*, grasstree, satellite, Eneabba, Western Australia, *Xanthorrhoea*

Introduction

A method for reconstructing bushfire history from fire marks on grasstree stems (*Xanthorrhoea* species) has been suggested, based on considerable sampling (over 500 stems) in dry woodlands and forests of south-western Australia (Ward 1996; Ward & Van Didden 1998; Ward *et al.* 1998; Lamont *et al.* 1999; Lamont & Ward 1999; Ward & Challinor 1999). The occurrence of past fires is shown by black marks on grasstree stems. These black marks, and intermediate vertical growth rings, are revealed by cleaning the charcoal from the stems. Chemical and histological work has confirmed that the black marks are caused by naphthoquinone, trapped in the vascular system of the needles by their sudden death (Colangelo *et al.* 2002). The most likely cause of such sudden death is bushfire.

With some grasstree records stretching back to before European settlement, the grasstree work has suggested consistently high bushfire frequency (2–4 year return period) generally prior to the 1930s, in dry *jarrah* (*Eucalyptus marginata*) and *tuart* forests (*Eucalyptus gomphocephala*), and in various woodlands (*Eucalyptus wandoo, Melaleuca* spp. and *Banksia* spp.).

These short fire intervals closely match those reported by early settlers and officials (Drummond 1844, Harris 1882, Hutchins 1916, Lane-Poole 1921, Bunbury & Morell 1930, Stoate & Helms 1938, Wallace 1966, Hallam 1975, 1985, 2002, Ward 1997, Abbott 2003, Hunt 2006), and given by members of the current *Nyoongar* (Aboriginal) community (Eades 1999, Wilkes 2006, Hume 2006). They also match the implications of bushfire behaviour drawn from some mathematical modelling using Percolation Theory. Patchy burning of between a quarter and a third of an area each year prevents broad fire fronts developing (Loehle 2004).

An understanding of history, in particular past human activities, is essential to ecology at the landscape scale (Naveh & Lieberman 1994; Swetnam *et al.* 1999; Burel & Baudry 2003). Some authors correctly point out problems with historical approaches (*e.g.* Miller *et al.* 2007), but this does not mean that all history should be discarded. Problems can arise with statistical approaches to ecology, but this does not mean that one should discard all statistics. Drawing on philosophy, the word consilience (Whewell 1840) comes to mind. It means a 'jumping together' of inductive evidence from a range of independent sources. There has been a call for greater recognition of the importance of consilience, in that scientists need, in their models and theories, the four qualities of parsimony, generality, consilience, and predictive ability (Wilson 1998).

Since its first publication (Ward 1996), there has been some questioning of the validity of the grasstree technique. Some of these criticisms have been in the political arena, so lie outside the scope of this journal. Other critics are research workers (Enright *et al.* 2005; Miller *et al.* 2007), who are concerned because fire histories reconstructed from grasstree stems contradict previous estimates of past fire intervals, derived from a seedbank model (Enright *et al.* 1998), or estimates of bushfire dates derived from satellite images. In this paper I focus on one of the critiques (Miller *et al.* 2007). Brief comment has already been made on the other (Ward 2006).

Miller *et al* (2007) (from here also referred to as 'the authors') compared the fire dates derived from grasstrees in *kwongan* heath at Beekeepers' Reserve, Eneabba, over a thirty year period (1973–2002 inclusive), against their interpretation of satellite photographs taken over the same site on clear days in August/September. From these data, they concluded that the fire dates derived from grasstrees showed little better than random association with those derived from satellite images, and are therefore unreliable. Miller *et al* (2007) cautioned against applying grasstree interpretation as an aid to bushfire management. Without further satellite interpretation, Miller *et al* (2007) extrapolated that caution to the more southerly vegetation, such as *jarrah* forest, sampled in previous grasstree work (Ward 1996; Ward & Van Didden 1998). They suggested that some past fire intervals, estimated from grasstrees, are too short for the survival of some plants. Miller *et al* (2007) also claimed that *kwongan* heath does not accumulate enough fuel to carry fire at the short intervals (3–5 years) often shown by the grasstrees. This paper examines these criticisms, and arrives at other conclusions.

Methods

As a first step, the raw data used by Miller *et al* (2007) were carefully checked against copies of the field sheets. Where found, errors and omissions were corrected.

Secondly, the logic used by Miller *et al* (2007) in defining agreement between fire dates derived from grasstrees, and those derived from satellite images, was evaluated. The authors, in their main contingency tables [Table 2 of Miller *et al* (2007), which uses the term 'confusion matrix'] only allow agreement when the grasstree and the satellite data show exactly the same calendar year. In this paper a different reasoning is used.

Satellite images taken in August/September will show, as new fires, those that occurred since the previous August/September, a period which straddles two calendar years. Miller *et al* (2007) note this, but do not use it in their reasoning. In *kwongan*, fires are now more likely in summer, but can occur at any time of year. For example, a fire first noted on a satellite image in calendar year 2000, may have occurred in 2000, or in 1999.

Similarly, due to the fire season straddling two calendar years, if a fire shown on a grasstree stem is dated as, say, 2000, this means it could have occurred in the fire season 1999/2000, or 2000/2001. Based on this reasoning, in this study, grasstree fire dates were allowed a tolerance of a calendar year either way, and fires dated from satellite images a year's extension backwards. Contingency tables were created using these wider, and more reasonable, tolerances for agreement.

Satellite images, due to resolution problems, will consistently fail to show very small fires (Price *et al.* 2003). In Beekeepers' Reserve, at Eneabba, such small fires could occur on individual grasstrees, or small groups, especially in winter, due to ignition by beekeepers, or wildflower pickers, or kangaroo shooters. Miller *et al* (2007) do concede the 'possibility of some error' in the satellite fire record, including the failure to show individual grasstree ignitions, but then use the satellite record as the benchmark 'truth'. In this paper I make no prior assumption on 'truth'. Hence, the terms 'agreement' and 'disagreement' are used when comparing grasstree fire records with those interpreted from satellite imagery, rather than the authors' terms 'true-positive, false-negative' *etc.*, which give a misleading air of certainty to the fire dates derived from satellite images.

Thirdly, a statistical method used by Miller *et al* (2007) was reviewed. The authors subjected their 'confusion matrices' to analysis using the κ (kappa) statistic (Galton 1892; Cohen 1960; Landis & Koch 1977). This seems to be a technique commonly used in the educational, psychological, and medical fields, but is a weak statistic, in that its sampling distribution is unknown, so one can never be sure of the significance of a given value. It has recently been criticized (Allouche *et al.* 2006). The best that can be done with it is to refer, as the authors do, to a significance table given in Landis & Koch (1977).

Unfortunately, this table is a matter of opinion, as its originators admit, saying that it is '*clearly arbitrary*', and intended only as a '*benchmark*' for discussion of a specific example given by them. This specific example involved allocation of patients, by two neurologists, into four classes. In the words of a seminal author on the kappa coefficient (Cohen 1960) *'it is generally of little value to test κ for significance'*. In fact it is impossible (Allouche *et al.* 2006).

Miller *et al* (2007) also refer to Fielding & Bell (1997), who reviewed methods for assessing prediction errors by ecological models. In that review, a plethora (13) of untestable statistics is given. The thrust of the Fielding & Bell (1997) paper is, in their own words, '*to adopt a pragmatic approach to model building in which we concentrate on the model's accuracy and usefulness, rather than testing the statistical validity of the model*'. It is not clear why the authors considered this relevant to their methods.

In this paper, the null hypothesis of a real difference between fire dates derived from grasstrees, and those derived from satellite images, for the last three decades of the twentieth century, is tested. The first step in this was to cast the data into a set of contingency tables, using the corrected data, as shown in Table 1. Although the χ-squared statistic (Pearson 1904; Fisher 1944) is often used to test such tables for dissociation between the two classificatory variables, it has been suggested that, where there is spatial autocorrelation, the probability of a Type I error may be underestimated (Legendre 1993).

In the Eneabba data, there is possible spatial autocorrelation, in that grasstrees are contagiously flammable. Five grasstrees, within a few metres of each other, were examined at each site. If one burned, then there was a likelihood that one or more of the others would also burn. To overcome this potential source of error, the data for each decade were split into five separate contingency tables, each containing only one grasstree from each site.

In the analysis of fire ecology, presence and absence of fire are equally important, and so deserve equal attention in methodology. Given the several years usually needed for enough fuel to accumulate, and the often haphazard nature of ignition, the occurrence of fire will nearly always be rarer than its absence, but this is no reason to regard fire presence as more ecologically, or statistically, important than fire absence. In this paper, agreement on fire presence and fire absence are given equal methodological status, whilst recognizing that the latter is usually more common than the former.

There is an inherent cumulative error in the grasstree dating method as one moves down the stem. Due to the rain solubility of the growth rings, growth rates can usually only be estimated near the top, and are then extrapolated back in time. Previous work (Lamont & Downes 1979) suggests that grasstrees grow at a constant rate throughout their life, but even a few millimetres error in estimated annual growth rate can lead to a much larger error lower down the stem, that is to say, further back in the past. This cumulative error definitely applies to the estimated calendar years of fires. It varies in its effect on fire interval estimates. For longer fire intervals, say several decades, it can be significant. As fire interval estimates get shorter, the cumulative error between fires diminishes. When fire intervals are only a few years, the error is abolished, due to rounding to the nearest whole year.

Table 1

Contingency tables showing the data, corrected for errors and omissions in Miller *et al.* (2007). The method for determining agreement between grasstrees and satellite imagery is as explained in this paper. As in Miller *et al.* (2007), (a) is the entire study period 1973–2002; (b) 1993–2002; (c) 1983–1992; and d) 1973–1982.

		Satellite Record		
		+	–	Sum
(a) Grasstree record	+	97	115	212
	–	103	2535	2638
	Sum	200	2650	2850
(b) Grasstree record	+	58	11	69
	–	42	839	881
	Sum	100	850	950
(c) Grasstree record	+	22	45	67
	–	33	850	883
	Sum	55	895	950
(d) Grasstree record	+	17	59	76
	–	28	846	874
	Sum	45	905	950

In their paper, Miller *et al* (2007) briefly mention fire intervals, but concentrate on fire dates. Yet one of their criticisms is that the fire intervals estimated from grasstrees are too short for the survival of some plants. In contrast, this paper examines fire intervals in some detail, comparing those shown by the grasstrees, with those shown by the satellite images.

In Beekeepers' Reserve, while cleaning charcoal off grasstree stems to reveal fires over the past three decades, I also opportunistically recorded fire marks back to the 1920s on some older grasstrees. These data were given to the authors at the time, but were not used in their analysis. To set the three decades of data examined by the authors in temporal context, this present paper compares them with fire intervals derived from these older fire marks.

Results

The contingency tables ('confusion matrices') presented by the authors as their Table 2, and based on the data in their Figure 2, have errors. Miller *et al* (2007) say that the analysis includes 20 sites, each with 5

Table 2

Contingency tables for the data split into five subsets, to avoid spatial autocorrelation within sites. Only one of the five grasstrees at each of the 19 sites (sites 8 and 18 omitted) is used in each table. The conventional labeling for cells is used, that is the top row as a and **b**, the second row as **c** and **d**. The expected count under the null hypothesis of random distribution is given in brackets, rounded to an integer. In a few cases, where it is close to the observed value, a decimal place is included.

		a	b	c	d	Σ
Grasstrees (1, 6, 11 …)	1973–82	2 (1)	16 (17)	7 (8)	165 (164)	190
	1983–92	7 (1)	7 (13)	3 (9)	173 (167)	190
	1993–02	11 (1)	2 (12)	9 (19)	168 (158)	190
Grasstrees (2, 7, 12 …)	1973–82	2 (1)	10 (11)	7 (8)	171 (170)	190
	1983–92	6 (1)	9 (14)	5 (10)	170 (165)	190
	1993–02	12 (2)	3 (13)	8 (18)	167 (157)	190
Grasstrees (3, 9, 13 …)						
	1973–82	4 (1)	9 (12)	4 (7)	173 (170)	190
	1983–92	5 (1)	11 (16)	5 (9)	169 (165)	190
	1993–02	11 (1)	3 (13)	9 (19)	167 (157)	190
Grasstrees (4, 10, 14 …)	1973–82	5 (1)	13 (17)	4 (8)	168 (164)	190
	1983–92	5 (1)	10 (14)	6 (10)	179 (175)	190
	1993–02	13 (1)	1 (13)	7 (19)	169 (157)	190
Grasstrees (5, 11, 15 …)	1973–82	4 (1)	11 (14)	5 (8)	170 (167)	190
	1983–92	1 (.8)	12 (12.2)	10 (10.2)	167 (166.8)	190
	1993–02	11 (1)	2 (12)	8 (18)	169 (159)	190

Table 3

The data of Table 2 converted to signs. Plus (+) where the observed count exceeds the expected, and minus (–) where it does not.

		a	b	c	d
Grasstrees (1, 6, 11...)	1973–82	+	–	–	+
	1983–92	+	–	–	+
	1993–02	+	–	–	+
Grasstrees (2, 7, 12 ...)	1973–82	+	–	–	+
	1983–92	+	–	–	+
	1993–02	+	–	–	+
Grasstrees (3, 9, 13 ...)	1973–82	+	–	–	+
	1983–92	+	–	–	+
	1993–02	+	–	–	+
Grasstrees (4, 10, 14 ...)	1973–82	+	–	–	+
	1983–92	+	–	–	+
	1993–02	+	–	–	+
Grasstrees (5, 11, 15 ...)	1973–82	+	–	–	+
	1983–92	+	–	–	+
	1993–02	+	–	–	+

In a contingency table, comparing observed with expected fire occurrence and absence, the probability of a perfect match is small. In a 2 X 2 table, where there is not a perfect match between observed and expected counts, adjacent cells must have opposite signs, and diagonal cells the same sign. Therefore the probability of the pattern (+ – – +) is less than 0.5, so the probability of that pattern occurring 15 times in succession is less than $(0.5)^{15}$, or approximately .00003. We may reject the hypothesis of random allocation to cells, and conclude there is a significant pattern of agreement between grasstree and satellite fire dates, by both mutual presence of fire, and mutual absence.

grasstrees, over a period of 30 years, so giving a grand total of 3000 observations, or 1000 for each decade. Grasstree cleaning took place at 21 sites, but in their Figure 2 only 19 sites are shown, sites 8 & 18 being omitted. The authors only mention the omission of one unspecified site, due to satellite uncertainty. If we take the authors' Figure 2 as a basis, with only 19 sites included, then the correct grand total of observations for the data in Table 2 is only 2850, and only 950 for each decade.

There are other errors, for example the omission of eight grasstree records in Sites 19, 20 & 21, in which grasstrees and satellite agree, on the field sheets, that there was a fire. A further four fires which appeared on grasstrees within a calendar year of the satellite estimate (Sites 10 & 21) were also omitted by the authors.

With the authors' errors and omissions corrected, and the more reasonable definition of 'agreement' applied, my Table 1 gives the revised contingency tables. Table 2 shows the data split into five separate contingency tables, to avoid autocorrelation. Table 3, shows the data converted to signs (+ or –).

Although there is some agreement between fire dates derived from grasstrees and satellite photographs, it is not perfect. As noted by the authors, agreement is weaker as we move into the past. Where disagreement occurs, it may be due to errors in grasstree interpretation, or in satellite image interpretation, or in both. A pattern analysis of the numbers of fires identified by grasstrees and satellite imagery is given in Table 4.

Table 4

Pattern of the number of fires. Plus (+) means the grasstrees showed more fires than the satellite images; minus (–) means grasstrees showed fewer fires than satellite images. There were no cases of equal numbers.

	1973–82	1983–92	1993–02
Grasstrees (1, 6, 11...)	+	+	–
Grasstrees (2, 7, 12 ...)	+	+	–
Grasstrees (3, 9, 13 ...)	+	+	–
Grasstrees (4, 10, 14 ...)	+	+	–
Grasstrees (5, 11, 15 ...)	+	+	–

Assuming a small probability that grasstrees and satellites may identify exactly the same number of fires, the probability of the pattern (+ + –) occurring by chance is less than $(0.5)^3$. The probability of it occurring five times in succession by chance is less than $(0.5)^{15}$, or approximately .00003. We may reject the null hypothesis of chance occurrence, and conclude there is a real tendency for grasstrees to show more fires than the satellite images in the two earlier decades, and fewer in the last decade.

Table 5

Statistical summary of fire intervals shown by grasstrees and satellite images for the years 1973–2002. All 21 sites are included. We cannot reject the null hypothesis that the samples drawn by the two methods are from the same population ($p>.05$ by Mood's Median Test, and $p>.9$ for a t-test on the means).

Statistic	Grasstrees	Satellite Images
Mean	9.93	9.88
Standard Deviation	4.95	4.91
Standard Error or Mean	0.34	0.44
Skewness	0.85	0.58
Median	9	8
Minimum	3	2
Maximum	29	22
95% CI for Mean	9.27–10.59	9.01–10.75
95% CI for Median	8–10	8–9
N	218	125

As in Miller *et al.* (2007), all the above analyses concentrate on the calendar dates of the fires. Yet even if two successive dates from a grasstree stem are incorrect, the interval between them may be correct, although wrongly dated. As discussed above, for ecological understanding, the intervals between fires are more important than the exact date. I have, therefore, calculated the intervals between fires, for both grasstree and satellite methods, over the thirty years of the study. Key descriptive statistics are given in Table 5. Mood's Median Test and the t-test for means do not support rejection of the hypothesis that the means and medians are equal.

To give a longer term perspective, Table 6 compares the median fire intervals calculated from the grasstree data, including the data collected opportunistically, back to the 1920s, with the median fire intervals calculated from the authors' satellite interpretation over the three recent decades.

Figure 1 shows the interval data, for grasstrees back to the 1920s, and for satellite interpretation back to 1973.

Table 6

Descriptive statistics, by decade, for fire intervals from grasstrees and satellite data. Opportunistically collected grasstree data back to the 1920s are included. For the satellite data, there were no previous records from which to estimate fire intervals before the 1980s.

	Intervals from satellites				Intervals from grasstrees			
Decades	Min.	Median	Max.	N.	Min.	Median	Max.	N.
2000s	2	7	18	45	3	13.5	29	44
1990s	9	14	22	50	4	10	17	50
1980s "	6	8	8	30	3	8	21	85
1970s					3	6	16	67
1960s					2	5	21	66
1950s					1	4	18	54
1940s					2	3	10	33
1930s					2	2	9	18
1920s					2	4	6	3

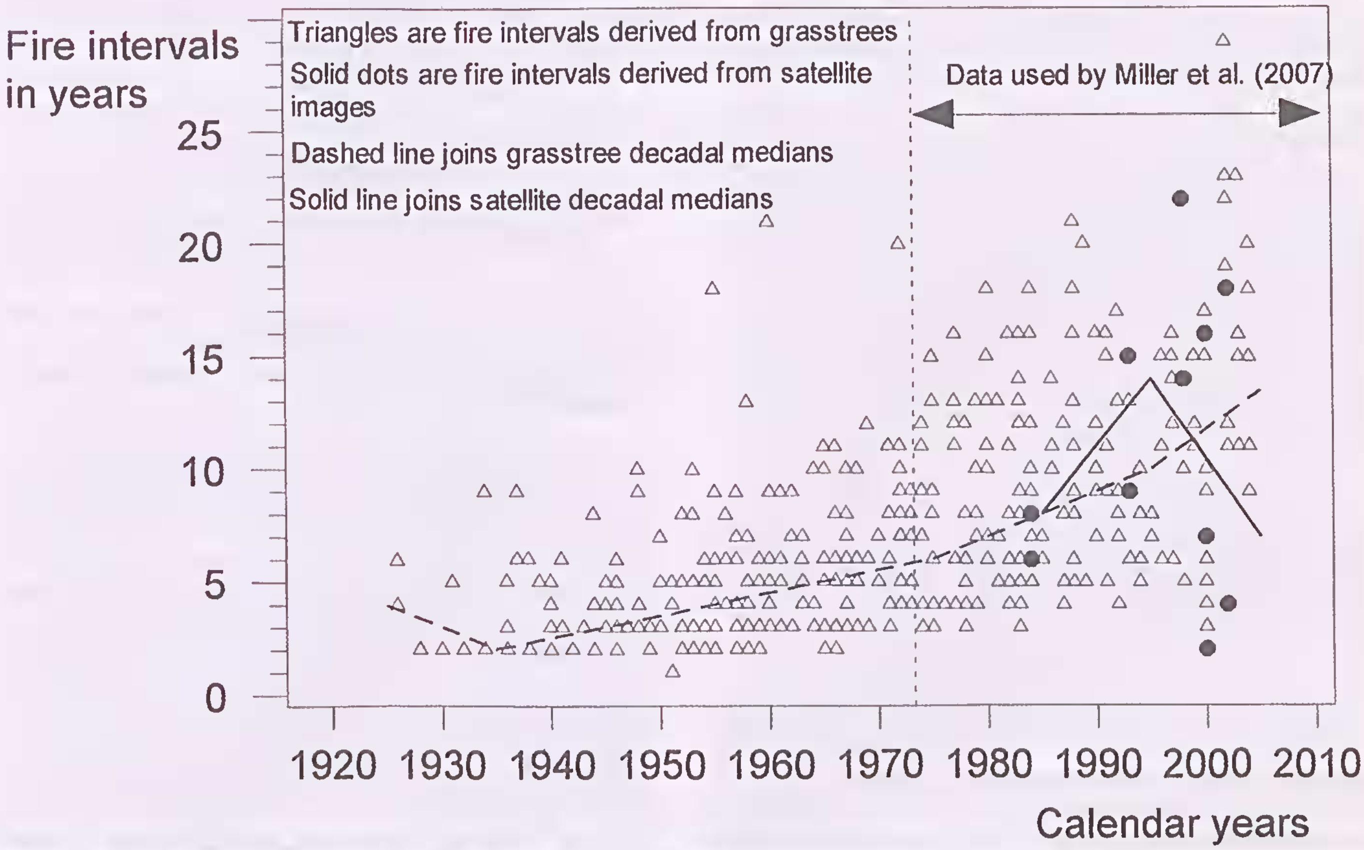

Figure 1. Interval data, for grasstrees back to the 1920s, and for satellite interpretation back to 1973. The median intervals from Tale 6 are included.

The median intervals from Table 6 are included. The grasstree data show a steadily lengthening of fire interval over the last century, which agrees with extensive previous grasstree data collected from more southerly vegetation, such as the *jarrah*, *tuart*, and *wandoo* forests (Ward 1996; Ward & Van Didden 1998; Ward *et al.* 1998, Ward 2001). The satellite fire intervals fall within the range of the grasstree fire intervals, and show a non-monotonic sequence of shorter, longer, then shorter median fire intervals in the *kwongan*.

Discussion

The grasstree cleaning at Eneabba was done in November 2004. In the following month, a very intense bushfire, much of it in long-unburnt fuel, burnt most of the Beekeepers' Reserve (Plozza & Groenhide 2005). Using the authors' method of satellite interpretation, this would have been incorrectly dated as a 2005 fire. Assuming, as the authors do, that fire dates derived from satellite photographs are 'true', grasstrees correctly showing the fire in 2004 would have been counted, by the authors, as 'false positives'. Similarly, grasstrees not showing the fire in 2005 would have been counted as 'false negatives'.

Local information is that such large summer fires were unknown in the past. According to a local farmer and fire fighter (Gillam 2005), up to the 1950s the *kwongan* heath in Beekeepers' Reserve was burnt as a mosaic of strips and patches, in winter or early spring, by mounted

Aboriginal kangaroo shooters, whose names are remembered. The shooters, now deceased, burnt to bring up winter grass, and so attract kangaroos. The winter grass was probably largely the native annual *Austrostipa compressa*, which still germinates profusely after fire in *kwongan*.

Remembering the importance of consilience, there are *djiridji* (*Macrozamia riedlii*) in the *kwongan*. Since *djiridji* are prolific nitrogen fixers for 3–4 years after fire (Grove *et al*. 1980), regular burning would have had an important benefit for them, and probably other *kwongan* plants. Under long fire exclusion this nitrogen fixation would be largely lost, and that loss exacerbated by occasional fierce summer fires, like that of December 2004, which must lose vast amounts of nitrogen over large areas, through gasification, volatilization, and ash convection (Wan *et al*. 2001).

I noted on the field sheets, and the authors comment on, the occurrence of fire marks under seemingly unburnt thatch. The authors suggest this supports their doubts about the grasstree method. Practical understanding of bushfire, and ways of fighting it, suggest otherwise. Firefighters will sometimes light grasstrees deliberately, to remove fuel from the path of an advancing bushfire. When they do so, they often dampen the thatch with short bursts from a hose, to keep the fire relatively mild. If, perhaps due to a wind shift, the main fire does not reach those grasstrees, there may be only part combustion of thatch, but a fire mark on the grasstree stem may nevertheless occur. Lighting grasstree thatch which is wet from rain, or even dew, can have a similar partial burning effect.

It is a common observation that, even when grasstrees do not burn, smoke drifting from a nearby fire can provoke flowering. The influence of smoke on grasstree flowering has been noted more formally (Gill & Ingwerson 1976). In the very poor sand of the *kwongan*, the effort of such flowering might, due to lack of nutrient, cause the sudden death of some green needles, so preventing the withdrawal of anthoquinone, and creating a black mark on the stem. Such sudden needle deaths would likely be more prevalent where there was no nutrient from ash, and where nearby legumes or *djiridji* had not been stimulated, by burning, into fixing nitrogen. As suggested by the authors, apparent fire marks on grasstrees which have not actually burnt, but have possibly been affected by smoke, are worth further investigation.

Without further satellite image interpretation, the authors have extrapolated their criticisms of the grasstree work to the *jarrah* forest, where there has long been a debate over the use of deliberate burning at relatively short intervals.

Jarrah is noted for its remarkable resistance to fire, even within a few years of germination, and forest experts have stated that it was, up to the 1920s, burnt every 2–3 years (Harris 1882; Hutchins 1916), or every 3–4 years (Hutchins 1916; Lane-Poole 1921; Stoate & Helms 1938), or every 2–4 years (Wallace 1966).

Stoate & Helms (1938) wrote that '*Jarrah as a species is remarkably resistant to fire*', and, referring to times before 1920, that '*it was unusual for any area of jarrah forest to escape periodic burning by at least a light ground fire for more than 3–4 years...*'. Hutchins (1916), who disliked forest fire, wrote that '*The jarrah forest, like most of the eucalypt forests, is liable to be burnt every two to three years...*'.

We should not ignore the well known rabbit plague of the 1920s and 1930s as a potential historical factor in changing *kwongan* fire frequency and intensity (Luke & McArthur 1977). More grass and forbs would support more frequent, mild, patchy fires, especially in winter or spring. Less fine fuel, and more woody fuel, would support more intense, less patchy fires, less frequently.

Miller *et al* (2007) say that fires in *kwongan* at 3–4 year intervals are incompatible with '*the absence of continuous fuels for carrying fire in shrublands*'. Yet, in their own Figure 2, their interpretation of satellite images shows fires in recent decades, at several sites, at 2 and 4 year intervals. It is important, in discussion of *kwongan* fuels, to distinguish between ground litter, and elevated shrubs. Driven by wind, a fire in heath can spread through the shrubs, even if there is sparse and discontinuous litter on the ground.

Conclusions

In *kwongan* heath, near Eneabba, Western Australia, a comparison between fire history reconstructed from grasstree stems, and that reconstructed from satellite images, shows overall agreement on fire dates, and close agreement on fire intervals, over the last three decades of the twentieth century. While agreement is not perfect, it is unlikely to occur by chance.

From the evidence available, it is not possible to say whether disagreements on fire dates are due to errors in satellite interpretation, or in grasstree interpretation, or in both. Of more ecological interest is the very close agreement between the mean fire intervals shown by the two methods, which supports the general validity of fire intervals derived from older grasstrees, extending back to the 1920s at Eneabba, and back to the 1850s elsewhere in the *kwongan*, at Yardanogo Reserve (Enright *et al*. 2005). These show regular burning at 2–5 year intervals.

There are, doubtless, errors in the grasstree data, as expected when measuring rough, contorted objects in the field. The grasstrees cleaned at Eneabba were notably smaller, and more contorted, than those cleaned further south (*e.g*. Ward & Van Didden 1998). To expect laboratory precision is unrealistic. At the same time, the grasstree technique can identify past small fires, including deliberate burning of individual grasstrees, or small groups thereof, by humans. Satellite images seem, as yet, to have insufficient resolution to detect such small scale burning.

In view of the history of human activities in Beekeepers' Reserve, past small scale burning is a likely reason for some of the disagreement between satellite and grasstree data. Using the authors' terminology, the satellite images are prone to 'false negatives', failing to identify small fires; and 'false positives', by failing to identify, within a burnt area, some grasstrees, or small patches, that have remained unburnt. Small scale burning in the past is also a likely cause of some disagreement between fire dates on individual grasstrees.

Bushfire ecology, behaviour, and history are very important aspects of West Australian ecology. They are inextricably entwined. The past fire intervals shown by grasstrees have potentially deep ecological significance in understanding changes in fire frequency, behaviour, and mosaic pattern since European arrival in Australia. More grasstree research is needed, and, for consilience, more research into historical information held in the local community.

On present evidence, frequent burning of a mosaic of interlocking strips and patches, in winter and early spring, is the most likely way to protect the *kwongan* from uncontrollable summer fires, burning on a broad front. We have much to learn about the significance of season, time of day, shade, humidity, soil moisture, slope, lighting pattern, wind speed, and wind changes, in using deliberate heath fires as a management tool, for both human safety and nature conservation. Aboriginal Elders may be able to help (Bird *et al.* 2008).

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